

Corn stubble height and residue placement in the northern US Corn Belt

Part I. Soil physical environment during winter

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Received 12 February 2001; received in revised form 31 August 2001; accepted 6 September 2001

Abstract

Management of crop residue is important for sustaining biological activity in soils during winter and promoting soil water recharge and early spring thaw in cold regions. This study assessed the impact of stubble height and residue placement in a corn (*Zea mays* L.) production system on the soil microclimate during winter in the northern Corn Belt of the USA. Residue treatments were established in a randomized block design after corn harvest in the autumn of 1993–1995 near Morris, MN. Corn was harvested using a combine that cut stalks at 60, 30 and approximately 0 cm above the soil surface and uniformly spread harvested residue over the soil. Treatments included: (1) 60 cm stubble, (2) 30 cm stubble, (3) 30 cm stubble with alternating bare and residue covered inter-rows, (4) 0 cm stubble, and (5) 0 cm stubble with all residue removed from the soil surface. Snow cover, depth of soil freezing and thawing, soil temperature and water content at various depths in the soil profile, and reflected global and net radiation were monitored during winter from November to March each year. Taller (60 cm) stubble trapped more snow, reduced the depth of frost penetration by at least 0.5 m, and hastened thawing of the soil profile by at least 25 days during winter as compared with short (0 cm) stubble and 0 cm stubble without residue treatments. Near surface, winter soil temperatures were moderated by at least 2 °C in the 60 cm stubble versus 0 cm stubble without residue treatments. Linear regression analysis suggested that 52, 93 and 40% of the variability in soil water recharge caused by residue treatments during successive winters, respectively, could be explained by differences in snow cover, soil water content and thaw depth among treatments. On clear days in autumn and spring, albedo was highest for the 0 cm stubble and lowest for the 0 cm stubble without residue treatments. Net radiation, however, was lowest for the 0 cm stubble and highest for the 0 cm stubble without residue treatments as compared with other residue treatments. Results from this study suggest that corn production systems in the northern Corn Belt which retain tall stubble on the soil surface will promote warmer soils during winter and earlier spring thaw as compared with those which retain short or no stubble on the soil surface. Published by Elsevier Science B.V.

Keywords: Soil temperature; Soil water; Soil frost; Soil thaw; Snow cover; Albedo; Net radiation

1. Introduction

Weather can have a profound influence on the biological, physical, and chemical processes of soils during winter in cold regions. Soil microbial popula-

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tions, for example generally decline as soils begin to freeze in winter and rapidly increase as soils begin to thaw in spring (Skogland et al., 1988). The ability of soil-dwelling organisms to survive at sub-freezing temperatures depends upon their mobility as well as on their physiological mechanisms for avoiding low-temperature stress. In addition, survival will depend on environmental conditions (such as soil water content and temperature) that prevail during the winter. These conditions, and therefore the physical environment of organisms, can be modified by tillage and crop residue management (Ellsbury et al., 1998).

Freezing and thawing processes that occur during winter can alter the physical properties of soil. The magnitude of change in many of the physical attributes of soil will depend on the duration and magnitude of sub-freezing temperatures, number of freeze–thaw cycles, and physical state of the soil at the time of freezing (Bryan, 1971; Hinman and Bisal, 1968). Aggregate stability, for example generally declines with repeated freezing and thawing (Edwards, 1991; Lehrs et al., 1991). Freezing and thawing can also influence chemical transport and ion concentrations within the soil profile. As fine-textured soils freeze, water and solutes tend to migrate from unfrozen to frozen regions within the soil profile (Gray and Granger, 1986). The extent of movement of water and solutes in the soil profile during freezing and thawing, however, will depend on the physical state of the soil, such as soil water content, at the time of freezing (Gray and Granger, 1986; Radke and Berry, 1998).

Tillage and crop residue management can influence soil physical properties and microclimate, both of which have far reaching implications for biological growth and diversity and environmental quality. Sharratt et al. (2000), for example reported that tillage and residue management practices that hasten thawing and drying of the soil could reduce runoff during spring thaw in the northern US Corn Belt. In the northern Corn Belt where strong winds result in considerable blowing of snow, management systems that aid in trapping snow will likely reduce frost penetration in the soil profile and moderate near surface temperatures (Benoit et al., 1986). Benoit et al. (1986) found that tillage management influenced snow cover and therefore soil temperatures during winter in the northern Corn Belt. They found that winter soil temperatures can be moderated

and depth of freezing reduced by minimizing autumn tillage operations or employing practices that retain residue on the soil surface in the autumn. Sharratt et al. (1998) found that managing residues after harvest in a no-tillage, corn production system in the northern Corn Belt could influence snow cover, frost depth, and soil water recharge. They found that residue left standing after harvest generally resulted in greater snow cover, reduced frost penetration into the soil profile, and warmer and wetter soils during winter as compared with removing residue from or distributing residue prostrate on the soil surface.

Corn residue management systems are needed in the northern US Corn Belt that have a moderating influence on the winter soil microclimate and thereby hasten sowing of crops in the spring. Corn stubble height can be altered at the time of harvest in the autumn and may be a strategy for enhancing warming of the soil during winter and thereby speed thawing of the soil in the spring. The purpose of this study was to determine the impact of altering corn stubble height and residue placement in the autumn on the soil microclimate during winter in the northern Corn Belt.

2. Materials and methods

This study assessed the soil microclimate during winter of various corn (*Zea mays* L.) residue management treatments in west central Minnesota near Morris (45°N, 95°W). Morris is typified by a continental climate with a mean annual air temperature of 5.5 °C and annual precipitation of 600 mm. Seasonal snowfall averages 1000 mm and daily minimum air temperatures are below 0 °C from 25 October to 15 April.

2.1. Experimental design

Treatments were established each autumn from 1993 to 1995 on a Barnes loam (Hapludoll in the USDA classification and Chernozem in the FAO classification) with a 2% east slope. Corn was sown in rows spaced 0.76 m apart in the spring of each year of the study. Grain was harvested in late October using a combine that cut corn stalks at 60 cm above the soil surface. The combine was equipped with a straw chopper that chopped and uniformly spread the harvested residue (stalks, leaves, tassels and cobs)

onto the soil surface. Corn residue treatments were established immediately after harvest. Treatments included: (1) 60 cm stubble—this treatment remained unaltered following grain harvest and was characterized by a combination of residue laying prostrate on the soil surface and standing stalks 60 cm in height; (2) 30 cm stubble—corn stalks that remained standing after grain harvest were cut at 30 cm above the soil surface using a combine that uniformly spread the cut stalk residue over the soil surface; (3) 30 cm stubble with banded residue—corn stalks that remained standing after harvest were cut at 30 cm above the soil surface using a combine. The loose residue laying prostrate on the soil surface of alternating inter-rows was then placed into adjacent inter-rows. Alternating inter-rows were devoid of residue while the soil surface of adjacent inter-rows was covered with corn residue; (4) 0 cm stubble—corn stalks that remained standing after harvest were cut near the soil surface using a combine. The cut stalk residue was uniformly spread over the soil surface; (5) 0 cm stubble without residue—corn stalks were cut close to the soil surface using a combine and all residue was then removed from the soil surface by hand raking.

The experimental design was a randomized complete block with three replications. Plots were 225 m² with sufficient alley between replications to ensure uniform residue distribution across the length of the plot. Corn residue characteristics of each plot were assessed in the spring following snowmelt (Table 1). Stubble height was determined by measuring the

height of 10 stalks in each plot. Percent residue cover was assessed by the line intersect method (Sloneker and Moldenhauer, 1977). Percent cover was calculated as an average of measurements taken across the two diagonals and perpendicular to rows of corn in each plot. Corn residue dry weight was determined by collecting, drying and weighing all residue (stalk, cob, leaf) within a 1 m² area in each plot. The density of standing stalks was 6 stalks m⁻² based on the number of stalks within a 4 m² area in each plot.

2.2. Soil microclimate

The microclimate of corn residue treatments was assessed throughout the winter. Snow cover and depth of frozen soil was measured thrice weekly in all plots. Snow depth was determined using snow stakes. The depth of frozen soil was assessed using frost tubes (Ricard et al., 1976) installed to a depth of 1.5 m. An extension of the frost tube above the soil surface allowed an additional assessment of snow cover. Soil water content was measured thrice weekly by neutron attenuation. Soil water content was assessed at 0.3 m depth intervals to 2.1 m in all plots using a neutron probe. In the 30 cm stubble with banded residue treatment, snow cover, frost depth, and soil water content was assessed in two adjacent inter-rows (one inter-row with residue and the other without residue). Net and reflected global radiation and soil temperature were measured every 60 s with the aid of a data logger. A net radiometer and pyranometer were suspended from a boom mounted 1 m above the soil surface in one replication of each treatment. The pyranometers were inverted to assess reflected global radiation. Radiometers were field-calibrated each year; radiometric comparisons were made with new factory-calibrated sensors over a uniform soil surface for several days prior to and after the study. Soil temperatures were measured midway between stubble rows in all plots with thermocouples installed at depths of 0.01, 0.05 and 0.10 m below the soil surface. Thermocouples were placed in adjacent inter-rows in the 30 cm stubble with banded residue treatment. Three thermocouples were placed and wired in parallel at each depth for acquiring a spatially averaged temperature. Air temperature, global radiation, wind speed and precipitation were measured at a microclimate station located about 100 m from the experiment site.

Table 1
Percent residue cover, residue biomass, and stubble height as influenced by corn residue management^a

Residue treatment ^b	Residue cover (%)	Biomass (g m ⁻²)	Stubble height (cm)
60 cm stubble	87 a	909 a	57 a
30 cm stubble	82 a	858 a	30 b
30 cm stubble, banded	69 b	1162 a	31 b
0 cm stubble	84 a	990 a	8 c
No stubble or residue	29 c	112 b	7 c

^a Means followed by same letter within a column are not significantly different.

^b Residue treatments were established after autumn harvest with data collected during the spring of 1993–1995 near Morris, MN.

Intermittent data logger failure resulted in loss of data for 13 days in 1994 (22 February–11 March) and for 20 days in 1995 (9–28 December).

The microclimate of the residue treatments was compared using an analysis of variance (Gomez and Gomez, 1984). In the event that treatment effects were significant ($P \leq 0.1$), means were compared using least significant difference.

3. Results and discussion

Two of the three winters of this study were characterized by colder and drier weather than is typical for the northern US Corn Belt. Air temperatures during the winter (November–March) of 1993–1994 and 1995–1996 were at least 2 °C below the 100-year average of –7 °C. Noteworthy was the cold January during both winters; the monthly air temperature was, respectively, 6 and 4 °C below the 100-year average of –13 °C. Precipitation during the winter of 1993–1994 and 1995–1996 was 20 and 60 mm below the 100-year average of 140 mm. Although precipitation was below average during these winters, total seasonal snowfall was 500 and 400 mm above the 100-year average of 900 mm.

3.1. Snow cover

The first snowfall occurred in successive winters on 5 November, 28 November, and 24 October. The first snowfall of winter generally melts in the northern Corn Belt, although snow occurring on 28 November 1994 persisted in all corn residue treatments until spring. Snow cover persisted in all treatments through the winter of 1993–1994 and 1995–1996 beginning on 25 November 1993 and 8 December 1995.

Depth of snow throughout each winter was influenced by residue treatments (Fig. 1 and Table 2). The depth of snow during the period of continuous snow cover averaged 55 cm for the 60 cm stubble treatment, 30 cm for the 30 cm stubble treatments, and 15 cm for the 0 cm stubble treatments across winters. Snow depth seldom exceeded the height of standing stubble throughout the winter due to the redistribution of snow by strong winds (average wind speed during winter was 4.5 m s⁻¹). Strong winds are common on the prairie landscape of the northern Corn Belt. Thus,

the height of stubble is an important factor in retaining snow. No differences in snow depth were apparent between the 30 cm stubble treatments or the 0 cm stubble treatments due to similar heights of standing stubble (Table 1).

The maximum depth of snow during each winter generally exceeded the height of stubble within each treatment (Table 2). The maximum depth of snow averaged across winters was 65 cm for the 60 cm stubble treatment, 40 cm for the 30 cm stubble treatments, and 30 cm for the 0 cm stubble treatments. Differences in snow depth among residue treatments appeared to influence the duration of snow cover (Table 2). Continuous snow cover on the 60 cm stubble treatment persisted longer (about 15 days averaged across years) than on the 0 cm stubble treatments. No difference in duration of continuous snow cover, however, was found between the 60 cm stubble and 30 cm stubble treatments in two of the three years of this study.

3.2. Soil frost

Freezing and thawing of agricultural soils in the northern Corn Belt begins in late October when daily minimum air temperatures typically remain below 0 °C. Freezing and thawing of the soil profile occurs until mid-November at which time some portion of the soil profile remains frozen for the duration of winter. Some portion of the soil profile remained frozen for the duration of the winter (freeze-up) beginning 13 November 1993, 22 November 1994, and 8 November 1995. These dates correspond to freeze-up of soils devoid of residue cover (0 cm stubble without residue treatment and bare inter-row of the 30 cm stubble with banded residue treatment). Freeze-up of soils with residue cover occurred at a later date. For example, for the winter of 1994–1995 and 1995–1996, freeze-up of the soil for all treatments with residue cover occurred on 23 November and 10 November, respectively. For the winter of 1993–1994, freeze-up of the soil for the 60 cm stubble and 30 cm stubble treatments occurred on 14 November and for the 0 cm stubble and 30 cm stubble with banded residue (inter-row with residue cover) treatments occurred on 20 November. Freeze-up was delayed 6 days in the latter two treatments (0 cm stubble and 30 cm stubble with banded residue) due to a greater amount of prostrate

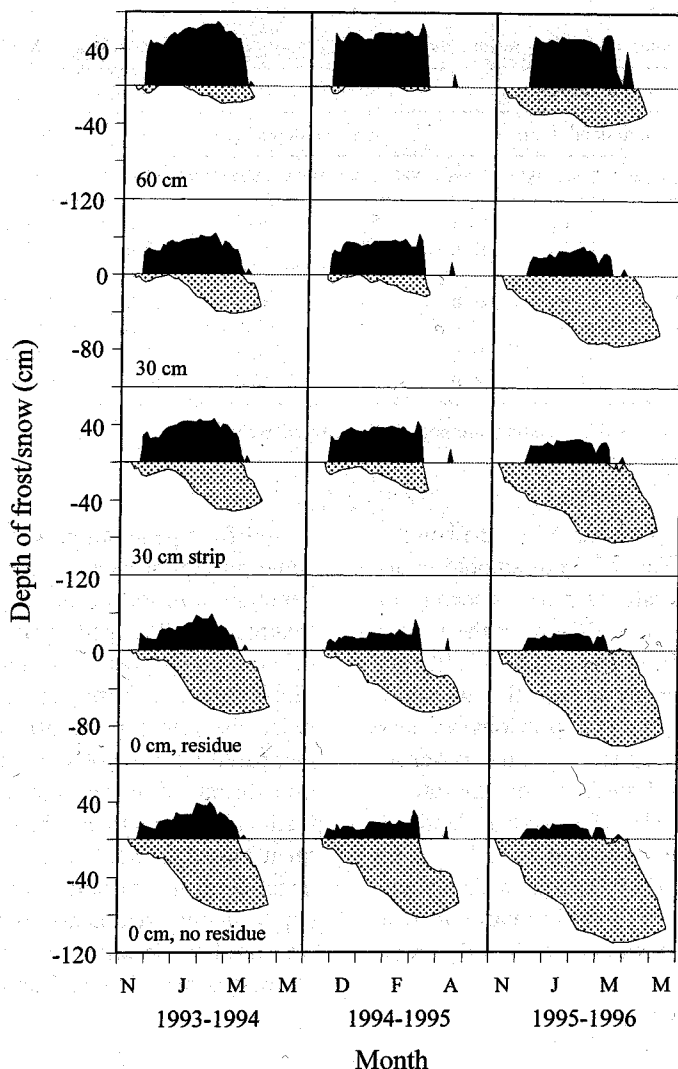


Fig. 1. Depth of snow cover (solid) and frost penetration (pattern) in soils with 60 cm stubble, 30 cm stubble, 30 cm stubble with banded residue (data for bare inter-row only), 0 cm stubble, and 0 cm stubble without residue cover across three winters near Morris, MN.

residue retarding heat loss from the soil surface as compared with the 60 cm stubble and 30 cm stubble treatments.

The depth of soil freezing was affected by weather across winters (Fig. 1). Averaged across residue treatments, the depth of soil freezing was at least 50% greater during the winter of 1995–1996 as compared to previous winters. Although the winter of 1995–1996 was equally as cold as the winter of 1993–1994 (2 °C below the 100-year average), seasonal snowfall was 10% less during the winter of 1995–1996. In addition,

snow cover was nearly 30% thinner during the 1995–1996 winter than the 1993–1994 winter (Table 2).

Depth of soil freezing was also influenced by corn stubble height and residue placement (Fig. 1). Taller stubble generally reduced frost penetration, largely as a result of the greater insulation provided by the thicker snowpack that developed in treatments with tall stubble. The maximum depth of soil frost was at least 50% less for the 60 cm stubble treatment as compared with the 30 cm stubble treatments (Table 3). Likewise, the maximum depth of frost on

Table 2

Snow cover characteristics as influenced by corn residue management during three winters near Morris, MN^a

Residue treatment	Snow cover variable								
	Maximum depth (cm)			Average depth ^b (cm)			Days ^b		
	1993–1994	1994–1995	1995–1996	1993–1994	1994–1995	1995–1996	1993–1994	1994–1995	1995–1996
60 cm stubble	70 a	70 a	58 a	55 a	56 a	51 a	114 a	105 a	107 a
30 cm stubble	44 b	44 b	33 b	32 b	33 b	22 b	112 ab	103 bc	90 b
30 cm stubble, banded									
Bare inter-row	47 b	44 b	27 b	36 b	34 b	21 b	112 ab	104 ab	90 b
Residue inter-row	45 b	44 b	33 b	34 b	32 b	23 b	112 ab	104 ab	90 b
0 cm stubble	39 c	33 c	21 c	23 c	16 c	15 c	110 b	102 c	72 c
0 cm stubble, no residue	40 c	31 c	16 d	24 c	14 c	10 d	111 b	102 c	72 c

^a Means followed by same letter within a column are not significantly different.^b For the period of continuous snow cover.

the 30 cm stubble treatments was 25% less than on the 0 cm stubble treatments. For the 0 cm stubble treatments, retention of prostrate residue appeared to influence soil frost depth, but only during the winter of 1995–1996 (Table 3). The winter of 1995–1996 was characterized by a less persistent and thinner snow cover as compared with the two previous winters (Table 2). Approximately 15 cm of snow cover is required to insulate the soil surface from the atmosphere (Sharratt et al., 1992). The average depth of snow on the 0 cm stubble treatments was 15 cm or more, except during the 1995–1996 winter. Therefore, prostrate residue may be beneficial in retarding frost penetration in soils during winters with little snow cover.

Soil frost penetration was near steady state during some portion of each winter. A constant rate of frost penetration in soil occurred simultaneously across all treatments and ranged from 0.4 to 1.4, 0.1 to 0.8 and 0.7 to 1.5 cm per day during successive winters (Table 3). Soil frost penetration occurred at nearly twice the rate for the 30 cm stubble treatments as compared with the 60 cm stubble treatment. In addition, the rate of frost penetration was 50% faster for the 0 cm stubble treatment than the 30 cm stubble treatment most winters. These differences in rate of frost penetration are attributed in part to differences in snow depth among treatments. Linear regression analysis was used to describe the relationship between rate of frost penetration and snow depth at the time of

Table 3

Soil frost characteristics as influenced by corn residue management during three winters near Morris, MN^a

Residue treatment	Soil frost variable								
	Maximum depth (cm)			Rate frost penetration ^b (cm per day)			Date of complete thaw ^c		
	1993–1994	1994–1995	1995–1996	1993–1994	1994–1995	1995–1996	1993–1994	1994–1995	1995–1996
60 cm stubble	18 a	7 a	40 a	0.4 a	0.1 a	0.7 a	83 a	72 a	108 a
30 cm stubble	41 b	22 b	75 b	0.9 b	0.4 b	1.2 ab	94 b	76 a	123 b
30 cm stubble, banded									
Bare inter-row	51 b	31 b	84 c	1.1 bc	0.5 b	1.2 b	97 b	78 a	125 b
Residue inter-row	48 b	29 b	86 c	1.1 bc	0.4 b	1.4 b	97 b	79 a	127 b
0 cm stubble	66 c	67 c	102 d	1.4 c	0.7 c	1.4 b	108 c	116 b	135 c
0 cm stubble, no residue	76 c	83 c	114 e	1.3 c	0.8 c	1.5 b	112 c	116 b	139 c

^a Means followed by same letter within a column are not significantly different.^b Determined from 6 to 25 January 1994; 20 January to 21 February 1995; 25 January to 12 February 1996.^c Day of year.

steady-state frost penetration. Snow depth accounted for 88, 97 and 95% of the variability in rate of frost penetration associated with residue treatments during successive winters.

Corn residue treatments also influenced the time of complete soil thaw (Fig. 1). The soil profile of the 60 cm stubble treatment thawed earlier (as much as 15 days) than the 30 cm stubble treatments during most winters. In addition, the soil profile of the 60 cm stubble treatment thawed at least 25 days (and as much as 40 days) earlier as compared with the 0 cm stubble treatments (Table 3).

3.3. Soil temperature

Average winter soil temperatures were highest for the 60 cm stubble treatment (Table 4). Indeed, soil temperatures for the 60 cm stubble treatment were more than 1.0 °C higher than the 0 cm stubble treatments and more than 0.5 °C higher than the 30 cm stubble treatments each winter. The 60 cm stubble treatment had higher seasonal temperatures due to less extreme minimum temperatures as compared with other residue management treatments. Minimum soil temperatures at the 1 cm depth in the 60 cm stubble treatment were more than 5 °C higher than the 0 cm stubble without residue treatment and at least 3.5 °C higher than the 0 cm stubble and 30 cm stubble with banded residue (bare inter-row only) treatments each winter. Maximum soil temperatures at the 1 cm depth, however, were 3–8 °C higher for the 0 cm stubble

without residue treatment than the 60 cm stubble treatment across winters. Little difference was observed in seasonal soil temperatures between the bare and residue inter-row of the 30 cm stubble with banded residue treatment. Although the soil temperature in the bare inter-row was more extreme, the higher maximum and lower minimum soil temperatures apparently compensated to result in nearly identical seasonal temperatures.

Residue treatments also influenced the time of occurrence of the minimum soil temperature. During the winter of 1993–1994, for example the lowest soil temperature (measured at 1 cm depth) for the 0 cm stubble treatments occurred on 19 January. The lowest soil temperature for the 60 cm stubble and 30 cm stubble treatments (including the residue inter-row of the 30 cm stubble treatment) occurred on 9 February, the coldest day (minimum air temperature was –36 °C) during winter. Although the minimum air temperature on 19 January was 2 °C higher than on 9 February, soil temperatures for the 0 cm stubble treatments were moderated by an additional 10 cm of snow cover on 9 February than on 19 January. During the 1994–1995 winter, the coldest day occurred on 8 March (minimum air temperature was –28 °C). Soil temperatures for the 0 cm stubble treatments, however, were lowest on 14 February, the second coldest day of winter (minimum air temperature was –26 °C). An additional 7 cm of snow cover moderated soil temperatures on 8 March as compared to temperatures on 14 February. Soil temperatures for the 30 cm

Table 4

Soil temperature characteristics as influenced by corn residue management during three winters (November–March) near Morris, MN^a

Residue treatment	Soil temperature variable (°C)								
	Maximum temperature ^b			Minimum temperature ^b			Average temperature ^c		
	1993–1994	1994–1995	1995–1996	1993–1994	1994–1995	1995–1996	1993–1994	1994–1995	1995–1996
60 cm stubble	6.1 bc	12.7 c	–0.1 a	–1.5 d	–4.0 c	–6.3 c	–0.4 d	0.2 d	–1.4 e
30 cm stubble	7.0 c	10.6 bc	–0.4 a	–3.1 c	–4.3 c	–6.4 c	–1.0 c	–0.4 cd	–2.4 d
30 cm stubble, banded									
Bare inter-row	15.4 d	17.0 d	8.0 b	–6.2 ab	–8.6 b	–10.5 b	–1.1 c	–0.6 c	–3.0 bc
Residue inter-row	2.2 c	6.3 a	1.0 a	–2.7 cd	–3.7 c	–6.4 c	–0.9 c	–0.9 c	–2.6 cd
0 cm stubble	4.0 ab	8.6 b	0.2 a	–5.0 b	–8.3 b	–10.2 b	–1.5 b	–2.5 b	–3.4 b
0 cm stubble, no residue	14.7 d	15.9 d	7.0 b	–6.7 a	–11.9 a	–12.6 a	–2.0 a	–3.6 a	–4.1 a

^a Means followed by same letter within a column are not significantly different.

^b 1 cm depth.

^c Averaged over the 1, 5 and 10 cm depths.

stubble treatments were lowest on 2 March. Although the minimum air temperature was 2 °C warmer on this day than on 14 February, snow cover on the 30 cm stubble treatments was 5 cm thinner on 2 March than on 14 February. Soil temperature for the 60 cm stubble treatment did not attain a minimum until near the time of complete snowmelt in mid-March. During the 1995–1996 winter, the lowest soil temperature for the 0 cm stubble treatments occurred on 3 February, the coldest day of winter (minimum air temperature was –35 °C). Snow cover on this day was about 15 cm for the 0 cm stubble treatments, 25 cm for the 30 cm stubble treatments and 55 cm for the 60 cm stubble treatment. The lowest soil temperature for the 30 cm stubble and 60 cm stubble treatments occurred on 7 December, the coldest day of autumn (minimum air temperature of –17 °C) prior to establishing seasonal snow cover.

Maximum soil temperatures occurred on nearly the same day for each of the residue treatments during winter. During the winter of 1993–1994, the highest temperature (1 cm depth) on all treatments was attained on 31 March. Although not the warmest day during winter (maximum air temperature was 13 °C on 22 March), maximum air temperature on 31 March was 8 °C. Soil temperatures on 22 March were possibly moderated by snowmelt that extended beyond this date about 5 days. During the 1994–1995 winter, soil temperatures for all treatments were highest on 17 March. This day was the warmest of the winter season (maximum air temperature of 17 °C) and occurred about 5 days after complete snowmelt.

During the 1995–1996 winter, the highest soil temperatures for all treatments, except the 60 cm stubble treatment, were attained on 16 March. This day was the warmest day of the spring (maximum air temperature of 8 °C) and occurred about 5 days after snowmelt. The highest soil temperature for the 60 cm stubble treatment occurred on 22 March, which was one of 3 days during March that snow cover was absent from this treatment.

3.4. Soil water

Residue treatments had little effect on over winter changes in soil water content. Seasonal increase in soil water storage was greater for one of the 0 cm stubble treatments than for all other treatments over two of the three winters (Table 5). Averaged across years, soil water storage in a 0.6 m profile increased by 7.7 cm for the 0 cm stubble treatment, 5.5 cm for the 0 cm stubble without residue treatment, and less than 4 cm for the 60 cm stubble and 30 cm stubble treatments. Similar trends among treatments were found in the seasonal increase in water content within a 2.1 m soil profile. For example, the 0 cm stubble treatment had the greatest increase in soil water content during the 1993–1994 winter (water storage in profile increased by 11.3 cm). Likewise, the 0 cm stubble without residue treatment had the greatest increase during the 1995–1996 winter (water storage in profile increased by –2.3 cm). During the winter of 1994–1995 and 1995–1996, however, water loss

Table 5

Soil water storage as influenced by corn residue management during three winters (November–March) near Morris, MN^a

Residue treatment	Increase in soil water storage (cm)					
	Seasonal ^b			Snowmelt ^c		
	1993–1994	1994–1995	1995–1996	1993–1994	1994–1995	1995–1996
60 cm stubble	5.2 ab	3.1 bc	0.7 a	4.2 ab	5.8 b	0.1 a
30 cm stubble	4.3 a	1.0 ab	5.7 b	2.2 a	2.8 a	0.8 ab
30 cm stubble, banded						
Bare inter-row	7.7 ab	0.8 ab	3.8 ab	5.5 b	2.2 a	1.4 b
Residue inter-row	4.4 ab	0 a	5.8 b	2.3 a	2.5 a	0.5 ab
0 cm stubble	12.6 c	5.2 c	5.3 b	7.1 b	2.0 a	0.3 a
0 cm stubble, no residue	8.9 bc	2.5 b	5.0 b	2.5 a	1.8 a	0.1 a

^a Means followed by same letter within a column are not significantly different.

^b For a 0.6 m soil profile from November to the end of spring snowmelt.

^c For a 0.6 m soil profile from beginning to end of spring snowmelt (15 February–28 March 1994; 6–15 March 1995; 8–22 March 1996).

occurred from the 2.1 m soil profile. Water loss from the soil profile during the winter of 1994–1995 ranged from 1.0 cm for the 30 cm stubble treatment to 6.6 cm for the bare inter-row of the 30 cm stubble with banded residue treatment. During the 1995–1996 winter, water loss from the soil profile ranged from 2.3 cm for the 0 cm stubble without residue treatment to 17.3 cm for the 60 cm stubble treatment. Water loss from the soil profile over winter resulted as a consequence of drainage of the lower soil profile (data not shown, but loss occurred below a depth of 0.75 m). Water loss was associated with a wetter soil profile at the commencement of the 1994–1995 and 1995–1996 winters than the first winter of this study. At the beginning of successive winters and averaged across treatments, volumetric water content to a depth of 2.1 m averaged 0.33, 0.45 and 0.44 $\text{m}^3 \text{m}^{-3}$. These findings support those of Benoit et al. (1988) who reported a net loss of water from the soil profile during winters in western Minnesota with initially wet autumns.

Recharge of the soil profile occurred as a result of spring snowmelt. Water storage in a 0.6 m soil profile increased by 4.0, 3.0 and 0.5 cm during each successive spring snowmelt period, respectively, when averaged across treatments. Recharge appeared to be greater during springs with thicker snow cover and deeper soil thaw. Averaged across residue treatments, depth of snow was 50, 45 and 25 cm at initiation of snowmelt in each successive spring while depth of soil thaw was 10, 10 and 2 cm at the end of the snowmelt period in each subsequent spring. Differences among

treatments in recharge during snowmelt did not appear consistent across winters (Table 5). In two of the three winters, however, the bare inter-row of the 30 cm stubble with banded residue treatment had greater recharge during snowmelt as compared with the 0 cm stubble without residue treatment. In this study, differences in snow cover and soil water content at the beginning of the snowmelt period and thaw depth at the end of the snowmelt period caused by residue management practices could explain some of the differences observed in recharge during snowmelt. Linear regression analysis suggested that 52, 93 and 40% of the variability in recharge caused by residue treatments during subsequent winters, respectively, could be explained by differences in snow cover, soil water content and thaw depth among treatments.

3.5. Radiation

Albedo (i.e. fraction of global radiation reflected from the surface) of treatments with residue cover decreased from 0.22 on clear autumn days to about 0.14 on clear spring days (Table 6). This decline in albedo is typically associated with bleaching and partial decomposition of the residue during the winter. The decline in albedo from autumn to spring was less evident for the 0 cm stubble without residue cover treatment, being 0.13 on clear autumn days and 0.08 on clear spring days. This decline in albedo may be associated with an increase in soil surface wetness; albedo on spring days was measured immediately following snowmelt and while the soil surface was

Table 6

Albedo and net radiation as influenced by corn residue management during three winters (November–March) near Morris, MN^a

Residue treatment	Albedo						Net radiation (MJ m^{-2} per day)					
	Autumn ^b			Spring ^c			Autumn ^b			Spring ^c		
	1993– 1994	1994– 1995	1995– 1996	1993– 1994	1994– 1995	1995– 1996	1993– 1994	1994– 1995	1995– 1996	1993– 1994	1994– 1995	1995– 1996
60 cm stubble	0.22 c	0.22 c	0.22 c	0.15 c	0.12 b	0.11 b	0.7 ab	1.2 a	0.9 bc	9.9 d	8.4 b	10.0 b
30 cm stubble	0.24 d	0.22 c	0.19 b	0.16 d	0.13 b	0.13 c	1.0 b	1.6 b	0.6 ab	8.6 b	8.0 a	10.0 b
30 cm stubble, band	0.20 b	0.20 b	0.20 b	0.14 b	0.13 b	0.10 b	1.1 c	1.6 b	1.0 bc	9.3 c	8.3 b	10.9 c
0 cm stubble	0.24 d	0.24 d	0.25 d	0.18 e	0.15 c	0.15 d	0.3 a	1.1 a	0.3 a	6.7 a	7.9 a	6.5 a
0 cm stubble, no residue	0.11 a	0.12 a	0.16 a	0.10 a	0.08 a	0.08 a	1.6 d	1.6 b	1.1 c	9.8 d	8.9 c	11.3 c

^a Means followed by same letter within a column are not significantly different.

^b For clear days prior to snow cover in autumn.

^c For clear days immediately after snowmelt in spring.

wet. Albedo during the winter was influenced by residue treatments. The albedo of residue treatments generally declined from 0 cm stubble > 30 cm stubble > 60 cm stubble > 30 cm stubble with banded residue > 0 cm stubble without residue. This ranking was not consistent over all winters. The albedo of the 0 cm stubble without residue treatment, however, was consistently smaller than other treatments. In addition, the albedo of the 30 cm stubble with banded residue was consistently equal to or smaller than the albedo of the 0 cm stubble, 30 cm stubble, and 60 cm stubble treatments.

Net radiation (i.e. energy available at the surface) for the 0 cm stubble without residue treatment generally equaled or exceeded net radiation of all other treatments (Table 6). Net radiation for the 0 cm stubble treatment was typically lower than other treatments, except in the autumn when net radiation for the 0 cm stubble and 30 or 60 cm stubble treatments were equal. Differences in net radiation were closely associated with differences in albedo among treatments. The greater net radiation for the 0 cm stubble without residue treatment indicates that more energy is available for evaporation or heating of the soil during early spring as compared with other treatments.

4. Conclusions

Corn residue management can have a profound influence on the soil microclimate during winter. The orientation of residue on the soil surface following harvest is critical in retaining and trapping snow during winter, particularly in regions such as the northern Corn Belt where strong winds result in considerable blowing of snow. Crop production practices that retain tall stubble on the soil surface after harvest will promote the development of a thick snowpack, thus aiding in retardation of heat loss and frost penetration in the soil profile. In addition, the heat retained in the soil profile during winter under tall stubble will aid in hastening spring thaw. Indeed, thawing of the soil profile was at least 25 days earlier over three winters where corn stalks were cut at 60 cm versus 0 cm above the soil surface. Despite the importance of tall stubble in promoting earlier spring thaw, net radiation and maximum soil temperatures in the early spring were generally higher for soils without residue

cover versus soils with residue cover. Therefore, future studies should be directed toward assessing the impact of residue management on the soil microclimate prior to spring planting.

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